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IGNITION-INDUCED FLOW DYNAMICS
IN BAGGED-CHARGE ARTILLERY

Albert W. Horst
Thomas C. Minor

August 1980

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US ARMY ARMAMENT RESEARCH AND DEVELOPMENT COMMAND
BALLISTIC RESEARCH LABORATORY
ABERDEEN PROVING GROUND, MARYLAND

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number) jmk Over recent years a number of efforts have been undertaken to develop interior ballistics models capable of treating ignition-induced, two-phase flow dynamics in gun chambers. A coincidental requirement was thus generated for experimental data usable for validation of such models. While data have been provided in the past on flame-front propagation as well as pressure-wave development in cased-ammunition guns, no direct information on flamespread in bagged charges was available. The initial confinement of the propellant bed and ignition		

species imposed by the bag, followed by allowable gas and solid phase mobilities in radial as well as axial directions upon bag rupture, could have a major impact on flamespread and flow dynamics during the early portion of the interior ballistic cycle. Such processes might significantly affect the usefulness of existing two-phase flow models formulated under an assumption of one-dimensional flow.

Data are presented which reflect the recent results of efforts to characterize flame-front propagation, propellant-bed mobility and pressure-wave development in bagged charges. Some experimental results are compared to numerical simulations, and inferences are drawn both about the adequacy of the models and about the basic phenomenology of bagged-charge performance.

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I. INTRODUCTION

The presence of pressure waves in gun chambers is thought to have been first recognized by Vielle¹ in the late 19th Century with his invention of the recording pressure gage. The significance of such phenomena was not appreciated, however, until some 50 years later, when R. H. Kent introduced the use of piezoelectric pressure gages^{2,3}. During the course of Kent's studies, he noted the importance of roles played by the ignition train, propellant-bed permeability, and the distribution of ullage in the gun chamber. These same parameters are receiving much attention today. Unfortunately, they passed all but forgotten by the charge design community until the late 1960's - early 1970's, when interest in such phenomena as pressure waves was necessarily revitalized in response to a series of gun ammunition malfunctions⁴⁻⁶, the causes of which were linked to ignition-induced, two-phase flow dynamics.

Since that time, a number of theoretical and experimental efforts have been undertaken to better understand the phenomenology of the gun interior ballistic cycle. Major advances have been made, largely as a result of the recognition of the interior ballistic cycle as an unsteady, two-phase flow problem, in which events occurring during the ignition/flamespread portion may have dramatic impact on the overall process. Thus a whole new field of two-phase flow, ignition and flamespread, interior ballistic modeling was founded, and with it the need for experimental

¹P. Vielle, quoted by Cranz in *"Lehrbuch der Ballistik,"* Volume II (Part I), Chapter 5, Springer Verlag, 1926.

²R. H. Kent, *"Study of Ignition of 155-mm Gun in Connection with Project KW250..."*, BRL Memorandum Report 4, Ballistic Research Laboratories, Aberdeen Proving Ground, MD, February 1935. (AD#493405)

³R. H. Kent, *"Study of Ignition of 155-mm Gun,"* BRL Report 22, Ballistic Research Laboratories, Aberdeen Proving Ground, MD, October 1935.(AD#494703)

⁴D. W. Culbertson, M. C. Shamblen, and J. S. O'Brasky, *"Investigation of 5" Gun In-Bore Ammunition Malfunctions,"* NWL TR-2624, Naval Weapons Laboratory, Dahlgren, VA, December 1971.

⁵I. W. May, E. V. Clarke, and H. Hassmann, *"A Case History: Gun Ignition Related Problems and Solutions for the XM198 Howitzer,"* Proceedings of the International Symposium of Gun Propellants, Picatinny Arsenal, October 1973.

⁶P. J. Olenick, *"Investigation of the 76-mm/62 Caliber Mark 75 Gun Mount Malfunction,"* NSWC/DL TR-3144, Naval Surface Weapons Center, Dahlgren, VA, October 1975.

data for model validation of a complexity far exceeding the capabilities of most existing range facilities. This report will deal with the progress, through November 1978, of this new field, particularly in respect to those problems singular to artillery bagged charges.

II. TECHNICAL DISCUSSION

A. The Phenomenology of the Gun Interior Ballistic Cycle

The overall gun interior ballistic cycle involves a complex interplay of physical and chemical processes. Classical pictures of the gun interior ballistic cycle typically divide it into several distinct phases: (1) ignition of the propellant charge; (2) combustion prior to projectile motion; (3) combustion accompanied by projectile motion; (4) gas expansion and projectile motion after propellant burnout; and (5) venting of gases from the tube after projectile exit. Simplifying assumptions often invoked to greatly facilitate model formulation include instantaneous, uniform ignition of the entire propellant bed, followed by a spacewise-averaged thermodynamic treatment of what is viewed to be a well-stirred mixture of propellant gas and particles. A simplified description of the pressure gradient is superimposed on this solution only for purposes of calculating maximum breech pressure and the force profile on the projectile base, integration of which yields velocity and travel profiles.

In actual practice, however, these artificially imposed divisions of the interior ballistic cycle may overlap significantly, and the implicit decoupling of this suggested sequence of events is far from correct. In particular, flow dynamics accompanying flamespread through the propellant charge (including both phases (1) and (2) as described previously) continue to exhibit significant impact on subsequent phases of the interior ballistic cycle. This influence is best demonstrated by specifically addressing the functioning of an idealized (through certainly not ideal) granular propellant charge, as shown in Figure 1. Typically an igniter system is electrically or mechanically initiated, leading to the venting of high-temperature, combustion products into a bed of granular propellant. The intensity and geometrical distribution of this output varies significantly with the system. The surfaces of nearby propellant grains are heated to a sufficient temperature to initiate combustion. Hot propellant gases then join those from the igniter to penetrate the rest of the bed, convectively heating the propellant and resulting in flamespread. During this phase, resistance to gas flow offered by the packed bed may result in large pressure gradients capable of leading to substantial propellant motion. In particular, localized ignition at the base of a cylindrical bed of propellant with ullage, or free space, present at the other end (between the charge and the projectile base) can lead to large forward velocities of both gas and solid phases.

Stagnation at the projectile base can then be accompanied by a substantial level of local pressurization, bed compaction, and perhaps even grain fracture⁷. In the limit, the ideal pressure-time curves shown in Figure 2 can give way to the very real examples of Figures 3 and 4, depicting overpressurizations which led to breechblows in 76-mm and 175-mm guns. These figures also illustrate a diagnostic procedure now employed by many ballisticians, whereby pressure-time data recorded at one end of the gun chamber are subtracted from corresponding data taken at the other end to yield the "pressure-difference profile." This curve not only provides a convenient, graphic portrayal of the evolution of longitudinal pressure waves in gun chambers, but also allows for application of quantitative assessment of their magnitude. If the forward gage output is subtracted from the breech pressure reading, one can record the presence and magnitude of a non-ideal, reverse gradient ($-\Delta P_i$ in Figures 3-4) associated with the stagnation event at the projectile base. While the occurrence of any pressure gradient other than that associated with the motion of the projectile down the tube can be considered fundamentally undesirable, one frequently occurs, and correlation of reverse pressure gradients ($-\Delta P_i$) with increases in maximum chamber pressures has helped to assess the sensitivity of a particular charge/weapon combination to pressure waves and, hence, to assess the inherent safety of the system.

This procedure has been useful on numerous occasions. However, a more rigorous understanding of those processes involved in the formation of pressure waves and their impact on the rest of the interior ballistic cycle is needed if one is to be able to make predictions about the performance and safety of new charge designs. Perhaps of even more importance is the need to provide a useful diagnostic capability with respect to anomalous behavior exhibited by existing charges. Accurate quantitative statements on any of these matters require the formulation of an adequate interior ballistic model which includes treatment of all important physical and chemical processes involved in flamespread, the formation of pressure waves, and their coupling with maximum chamber pressures*. For the experimentalist, this means that he is called upon first to assist in identifying those processes which must be considered in the physical scope of the model, and second to provide data for validation of the adequacy of the physical representation and numerical procedures.

⁷ A. W. Horst, I. W. May, and E. V. Clarke, "The Missing Link Between Pressure Waves and Breech-blows," 14th JANNAF Combustion Meeting, CPIA Publication 292, December 1977.

*This discussion ignores the problems of charge/projectile interface associated with transient loads imparted by gas and solid phases, be they from the propellant itself or from parasitics. There is no intention by the authors to slight the importance of this area; rather it is simply outside the bounds of the current discussion.

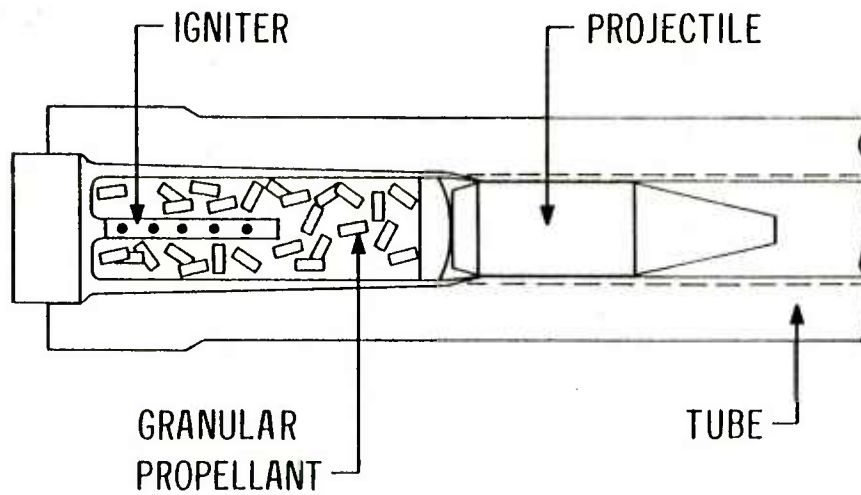


Figure 1. Schematic of Gun Propelling Charge

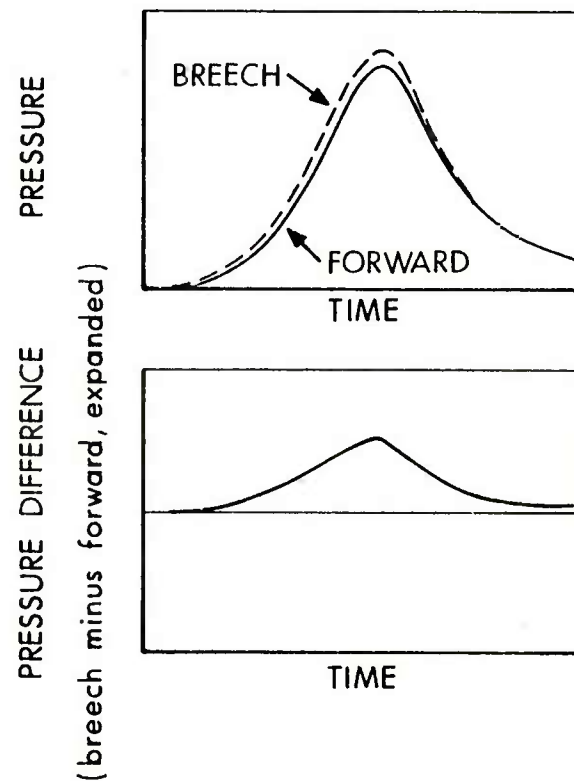


Figure 2. Pressure-Time and Pressure-Difference Profiles - Ideal

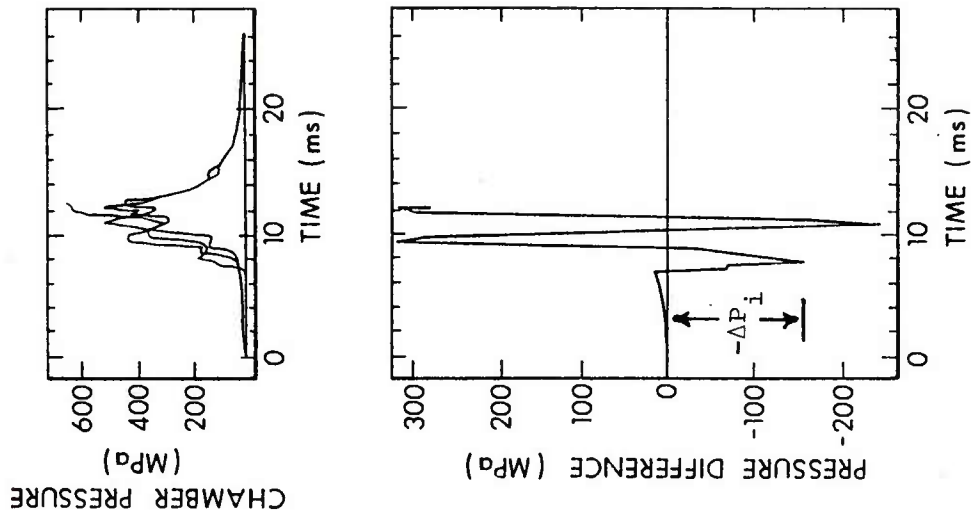


Figure 4. Chamber Pressures at Three Axial Locations and Pressure-Difference Profile, 175-mm Breechblow

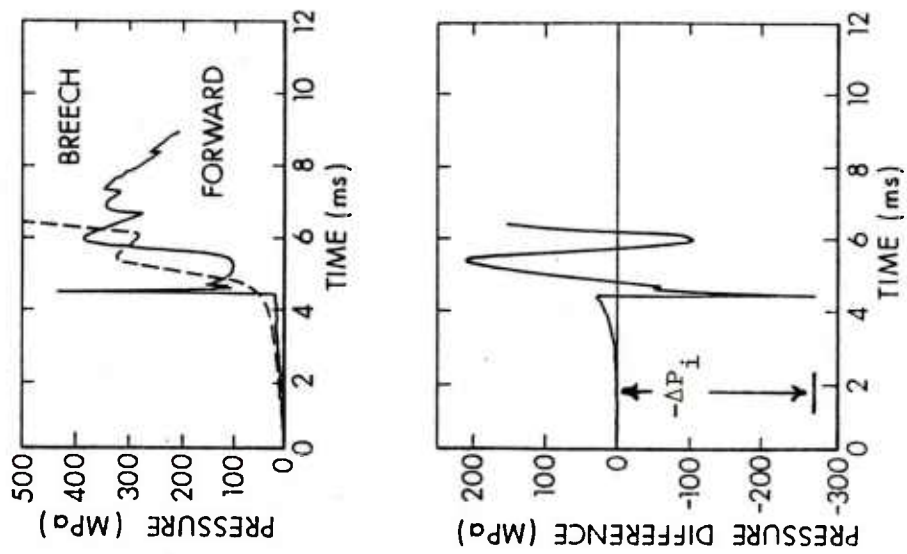


Figure 3. Pressure-Time and Pressure-Difference Profiles, 76-mm Breechblow

B. Recent Advances in Interior Ballistic Modeling

The modeling of unsteady, multi-phase flows is a vigorous field, with applications both numerous and diverse. A small sample of the nature and complexity of such work was recently revealed at an Army Research Office Workshop on Multi-phase Flows⁸. One subset of this field has been that of flamespread and combustion in a mobile, granular propellant bed. These studies are of particular interest in terms of their relevance to ignition transients, pressure waves, and even breechblows in Army artillery and tank guns. The works of several US flamespread modelers were reviewed in a Joint-Army-Navy-NASA-Air Force (JANNAF) Workshop⁹ several years earlier. Since that time, modeling of flamespread and pressure-wave phenomena in the gun environment has received further attention principally by Fisher¹⁰, Gough¹¹, and Kuo¹². Several other efforts^{13,14} recently sponsored by the US Army are addressing post-flamespread phenomena and, hence, are not relevant to the description of ignition/combustion-driven pressure waves and attendant problems.

⁸J. Chandra and C. Zoltani, editors, *Proceedings of ARO Workshop on Multiphase Flows*, U. S. Army Research Office and the Ballistic Research Laboratory, Aberdeen Proving Ground, MD, February 1978.

⁹K. K. Kuo, "A Summary of the JANNAF Workshop on Theoretical Modeling and Experimental Measurements of the Combustion and Fluid Flow Processes in Gun Propellant Charges," 13th JANNAF Combustion Meeting, CPIA Publication 281, December 1976.

¹⁰E. B. Fisher, "Quality Control of Continuously Produced Gun Propellant," Calspan Report No. SA-5913-X-1, Calspan Corporation, Buffalo, NY, August 1977.

¹¹P. S. Gough and F. J. Zwarts, "Some Fundamental Aspects of the Digital Simulation of Convective Burning in Porous Beds," AIAA Paper No. 77-855, AIAA/SAE 13th Propulsion Conference, July 1977.

¹²K. K. Kuo and J. H. Koo, "Transient Combustion in Granular Propellant Beds. Part 1: Theoretical Modeling and Numerical Solution of Transient Combustion Processes in Mobile Granular Propellant Beds," BRL CR 346, U. S. Army Ballistic Research Laboratory, Aberdeen Proving Ground, MD, August 1977. (AD#A044998)

¹³H. J. Gibeling, R. C. Buggeln and H. McDonald, "Development of a Two-Dimensional Implicit Interior Ballistics Code," AFBRL-CR-00411, Ballistic Research Laboratory, USA ARRADCOM, Aberdeen Proving Ground, MD, January 1980. (AD#A084092)

¹⁴A. C. Buckingham, "Modeling Additive and Hostile Particulate Influences in Gun Combustion Turbulent Erosion," CPIA Publication No. 308, Proceedings of the 16th JANNAF Combustion Meeting, December 1979.

Calculations included in this study were performed using the NOVA Code, developed by Paul Gough Associates.^{11,15-17} NOVA consists of a two-phase flow treatment of the gun interior ballistics cycle formulated under the assumption of "quasi-one-dimensional" flow, i.e., one dimensional flow with explicit treatment of area change. The balance equations describe the evolution of averages of flow properties accompanying changes in mass, momentum and energy and arising out of interactions associated with combustion, interphase drag and heat transfer. Constitutive laws include a covolume equation of state for the gas and an incompressible solid phase. Compaction of an aggregate of grains, however, is allowed, with granular stresses in excess of ambient gas pressure taken to be in accord with steady state measurements. Interphase drag is represented by reference to the empirical, steady state correlations of Ergun¹⁸ and Andersson¹⁹ for fixed and fluidized beds respectively. Interphase heat transfer is described similarly according to Denton²⁰ or Gelperin-Einstein²¹. Functioning of the igniter is included by specifying a pre-determined mass injection rate as a function of position and time. Flamespreading then follows from axial convection, with grain surface

¹⁵P. S. Gough and F. J. Zwarts, "Theoretical Model for Ignition of Gun Propellant," SRC-R-67, Space Research Corporation, North Troy, VT, December 1972.

¹⁶P. S. Gough, "Fundamental Investigation of the Interior Ballistics of Guns," IHCR 74-1, Naval Ordnance Station, Indian Head, MD, July 1974.

¹⁷P. S. Gough, "Computer Modeling of Interior Ballistics," IHCR 75-3, Naval Ordnance Station, Indian Head, MD, October 1975.

¹⁸S. Ergun, "Fluid Flow Through Packed Columns," Chem. Eng. Progr., Vol. 48, pp. 89-95, 1952.

¹⁹K. E. B. Andersson, "Pressure Drop in Ideal Fluidization," Chem. Eng. Sci., Vol. 15, pp. 276-297, 1961.

²⁰W. H. Denton, "General Discussion on Heat Transfer," Inst. Mech. Eng. and Am. Soc. Mech. Eng., London, 1951.

²¹N. I. Gelperin and V. G. Einstein, "Heat Transfer in Fluidized Beds," Fluidization, edited by J. F. Davidson and D. Harrison, Academic Press, 1971.

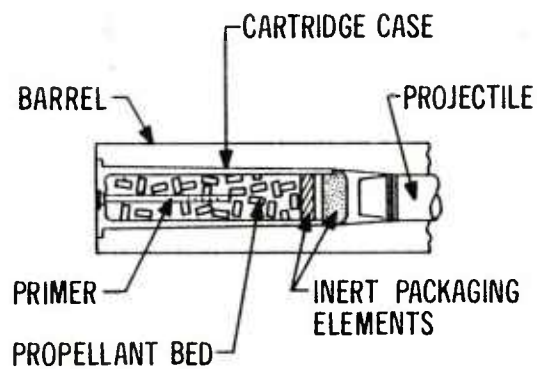
temperature being deduced from the heat transfer correlation and the unsteady heat conduction equation, and ignition based on a surface temperature criterion. In addition, internal boundaries defined by discontinuity in porosity are treated explicitly, and the forward external boundary reflects the inertial and compactibility characteristics of any inert, packaging elements present between the propellant bed and the base of the projectile. Solutions are obtained using an explicit finite difference scheme based on the method of MacCormack²² for points in the interior and the method of characteristics at internal and external boundaries.

C. The Cased-Ammunition Problem

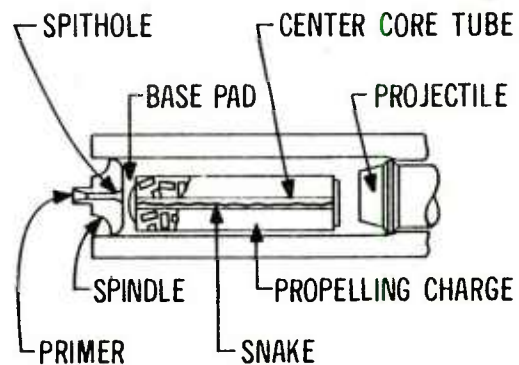
There exist many schemes for classifying gun-type weapons and their ammunition. Upon limiting the discussion to medium and large caliber weapons, we are left with two basic propelling charge configurations: cased and bagged charges (see Figure 5). In general, functioning is quite similar and as described previously. However, we now address some of the specific, geometry-induced differences which can significantly alter these processes. In cased ammunition, the propellant bed is normally situated such that no radial ullage exists. All free volume not associated with the interstices of the granular bed is located at the front of the charge. Compactible filler elements such as wads, spacers, or case closure plugs may be present, but actually offer very little resistance to motion of propellant gases or grains. Thus, large forward flow velocities are attainable prior to projectile motion, and, in fact, an extremely dynamic stagnation event can occur at the base of the projectile in the manner discussed. Radial motion of the solid phase is limited to that allowed by bed compactibility and may be inconsequential. However, radial gas flow from the high pressure bayonet primer of the type most often employed should be significant to the ignition process. Indeed, it is the intent of such primers to provide near simultaneous ignition in the axial mode, with radial flamespread being relatively innocuous with respect to the formation of deleterious pressure waves. Actual performance may deviate from this picture significantly.

Consider the Navy 5-inch, 54-caliber case gun, ammunition and gun chamber interface for which are schematically depicted in Figure 6. The relatively high amplitude pressure waves manifested in the experimental data of Figure 7 are believed, based on our understanding of the phenomenology as just described, to be a result of a somewhat localized ignition near the first row of primer ventholes, coupled with the large forward ullage present between propellant and projectile. Thus, despite

²²R. W. MacCormack, "The Effects of Viscosity in Hypervelocity Impact Cratering," AIAA Paper No. 69-354, AIAA 7th Aerospace Science Meeting 1969.



CASED AMMUNITION



BAGGED CHARGE

Figure 5. Typical Cased and Bagged-Charge Configurations

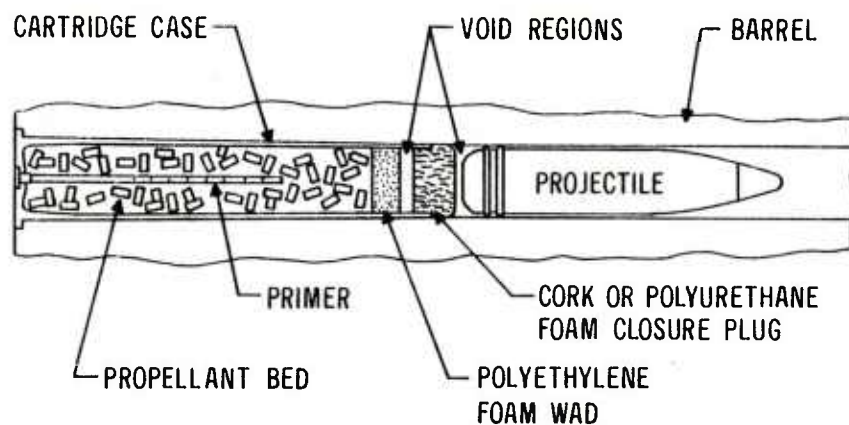


Figure 6. Schematic View of Propelling Charge and Projectile in Navy 5-Inch, 54-Caliber Gun

the presence of the long primer, flamespread in the propellant bed remains a largely one-dimensional process.

The NOVA Code has been applied to this configuration on numerous occasions. Results are presented here of a calculation based on input data all of which except the projectile engraving force/barrel resistance table were independently determined. A complete listing of these data and a discussion of techniques used to obtain them is available²³.

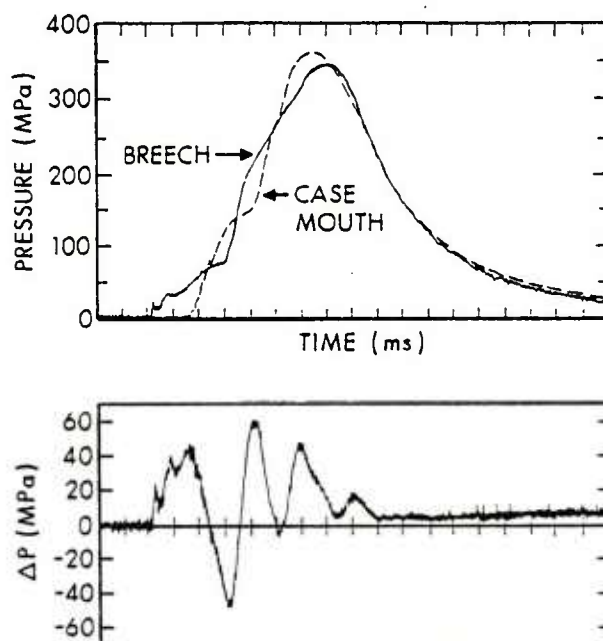


Figure 7. Typical Pressure-Time and Pressure-Difference Profiles (Experimental) for Navy 5-Inch, 54-Caliber Gun

²³A. W. Horst and F. W. Robbins, "Solid Propellant Gun Interior Ballistics Annual Report: FY76/TQ," IHTR-456, Naval Ordnance Station, Indian Head, MD, January 1977.

Figure 8 provides a comparison of predicted and experimental pressure-difference data, reflecting excellent qualitative and fairly good quantitative agreement. A similar comparison for flame propagation velocities is also possible for this configuration. Tests have been performed by East, et al²⁴⁻²⁶ at NSWC, Dahlgren, using a fiberglass breech assembly, transparent to x-rays (for studying grain and inert component motion) and to high-intensity light (allowing high-speed cinematography of flame propagation). Again, good agreement is found to exist between theory and experiment for flame and pressure propagation rates (Figure 9). Several other NOVA calculations of cased-ammunition configurations have been extremely encouraging, despite limitations imposed by the 1-D representation^{27,28}. However, it must be observed that these guns have differed essentially only in scale.

²⁴J. L. East and D. R. McClure, "Experimental Techniques for Investigating the Start-Up Ignition/Combustion Transients in Full-Scale Charge Assemblies," 11th JANNAF Combustion Meeting, CPIA Publication 261, December 1974.

²⁵J. L. East and D. R. McClure, "Experimental Studies of Ignition and Combustion in Naval Guns," 12th JANNAF Combustion Meeting, CPIA Publication 273, December 1975.

²⁶W. R. Burrell and J. L. East, "Effects of Production Packing Depth and Ignition Techniques on Propelling Charge Reaction and Projectile Response," NSWC/DL TR-3705, Naval Surface Weapons Center, Dahlgren, VA, April 1978.

²⁷A. W. Horst, T. C. Smith, and S. E. Mitchell, "Key Design Parameters in Controlling Gun Environment Pressure Wave Phenomena - Theory Versus Experiment," 13th JANNAF Combustion Meeting, CPIA Publication 281, December 1976.

²⁸A. W. Horst and P. S. Gough, "Influence of Propellant Packaging on Performance of Navy Case Gun Ammunition," Journal of Ballistics, Vol. 1, No. 3, pp. 229-258, 1977.

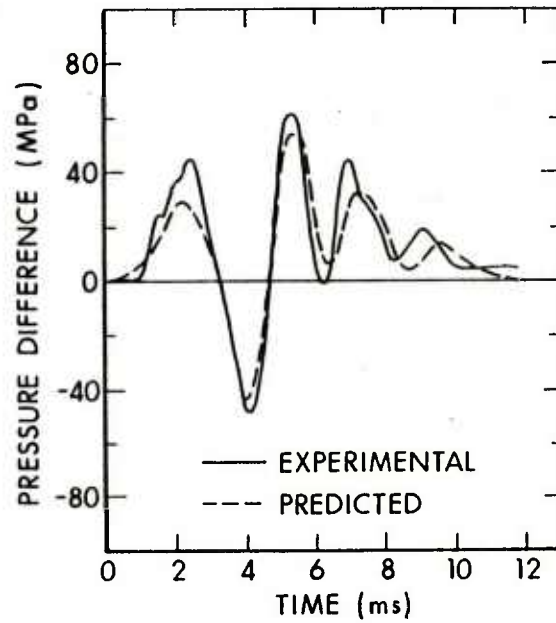


Figure 8. Comparison of Predicted and Experimental Pressure-Difference Profiles, Navy 5-Inch, 54-Caliber Gun

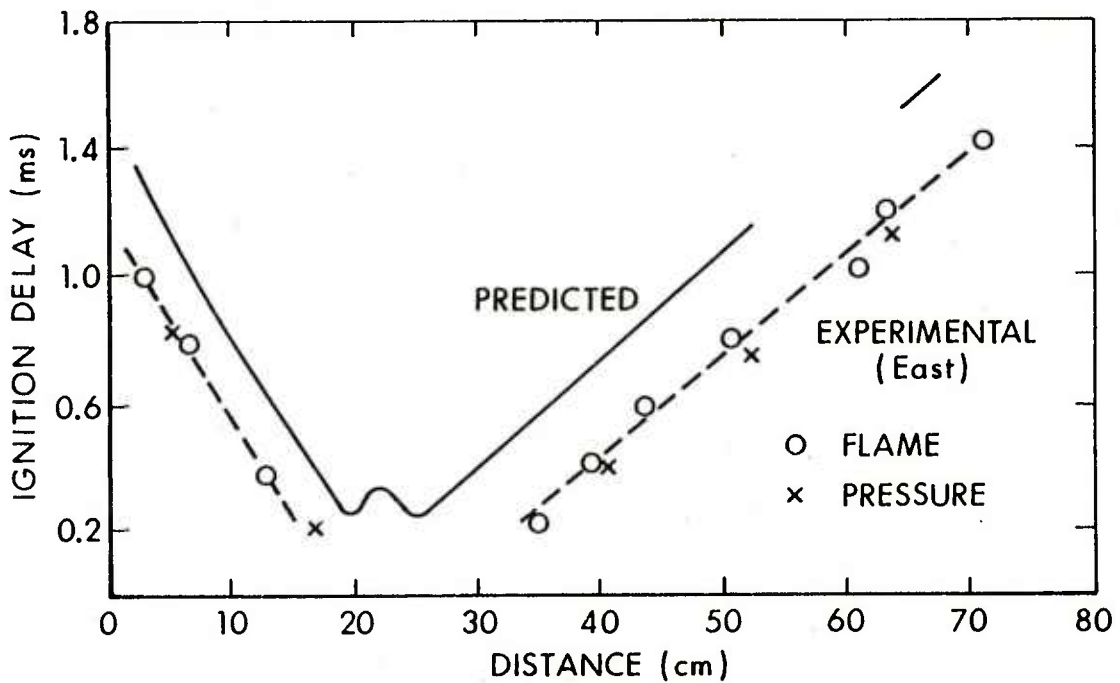


Figure 9. Flame-Front Propagation, Navy 5-Inch, 54-Caliber Gun

D. Bagged-Charge Phenomenology

Bagged charges, typically used in Army artillery, are so named because of the cloth bag which serves as an inexpensive, combustible encasement for the propellant charge. This bag is typically undersized with respect to internal chamber dimensions, both in respect to its length and diameter. This initial geometry can allow a variety of complicated flows to occur, depending on the configurational interface between the charge and the chamber. Prior to bag rupture, ignition gases may flow around the charge as well as through the bed. Once integrity of the bag is lost, significant radial velocities may occur in the solid phase as well. In actuality, the initial charge/chamber interface is not even axisymmetric. Additionally, bagged-charge igniter systems, be they basepad alone or centercore, function at much lower pressures than do bayonet primers and hence lead to greatly increased ignition delays when compared to cased ammunition performance. The impact of this delay is not well understood but is considered to be of potential significance to the overall flamespread process. Some of these features of bagged-charge phenomenology will be readdressed in greater detail later in this paper.

Application of one-dimensional models such as NOVA to bagged charges has generally yielded less than satisfying results²⁹. One illustrative example involves simulation of the 155-mm, M203, Propelling Charge (Zone 8) in the M198 Howitzer. Shown in detail in Figure 10, the M203 is a centercore-ignited, high-performance charge employing M30A1 Propellant. The results of a recent NOVA calculation based on a completely independently-determined data base for this charge³⁰ are compared to experimental data in Figures 11-13. The overall pressurization profiles are quite similar to experimental data. Detailed analysis of a comparison of predicted and observed pressure-difference profiles, however, reveals some disturbing features. First, we notice a strong, predicted positive difference (i.e., local pressurization at the breech end of the chamber) not observed experimentally. This prediction may be a consequence of the one-dimensional approximation, which requires that all basepad combustion products pass into the low permeability propellant bed, as opposed to venting around the charge external to the bag, rapidly equilibrating pressures throughout the chamber. The schematic representations of Figure 14 serve to clarify this point. This same configurational difference between NOVA and reality may also be responsible, in part, for the predicted,

²⁹A. W. Horst, C. W. Nelson and I. W. May, "Flame Spreading in Granular Propellant Beds: A Diagnostic Comparison of Theory to Experiment," AIAA Paper No. 77-856, AIAA/SAE 13th Propulsion Conference, July 1977.

³⁰A. W. Horst and T. R. Trafton, "NOVA Code Simulation of a 155-mm Howitzer: An Update," ARBRL-MR-02967, Ballistic Research Laboratory, USA ARRADCOM, Aberdeen Proving Ground, MD, October 1979. (AD#A079893)

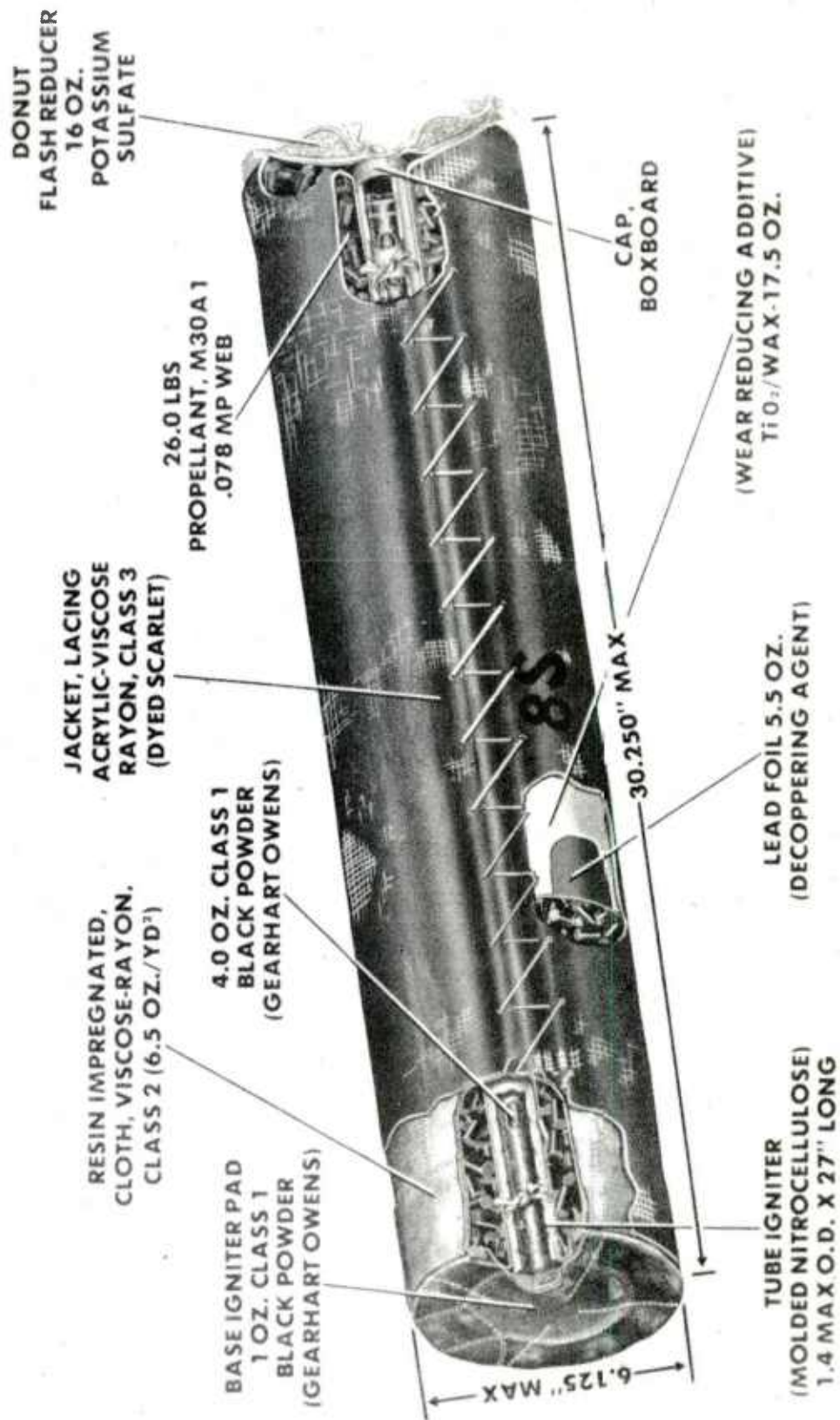


Figure 10. 155-mm, M203, Propelling Charge

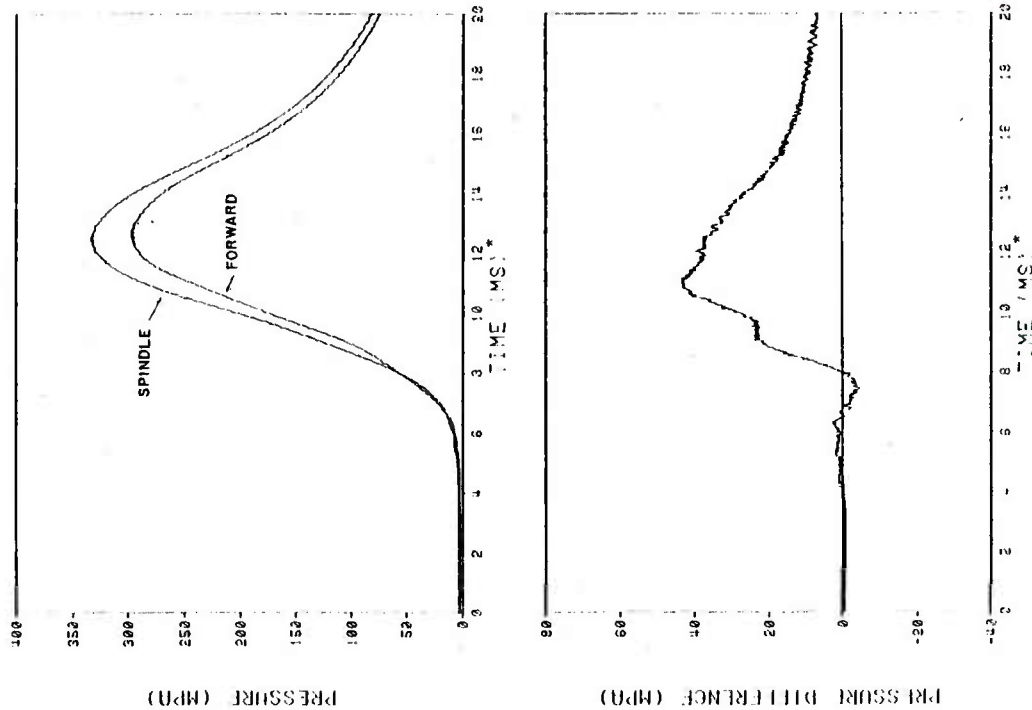


Figure 11. Experimental Pressurization Profiles,
M203 Propelling Charge, 25-mm Standoff

*Arbitrary zero reference time

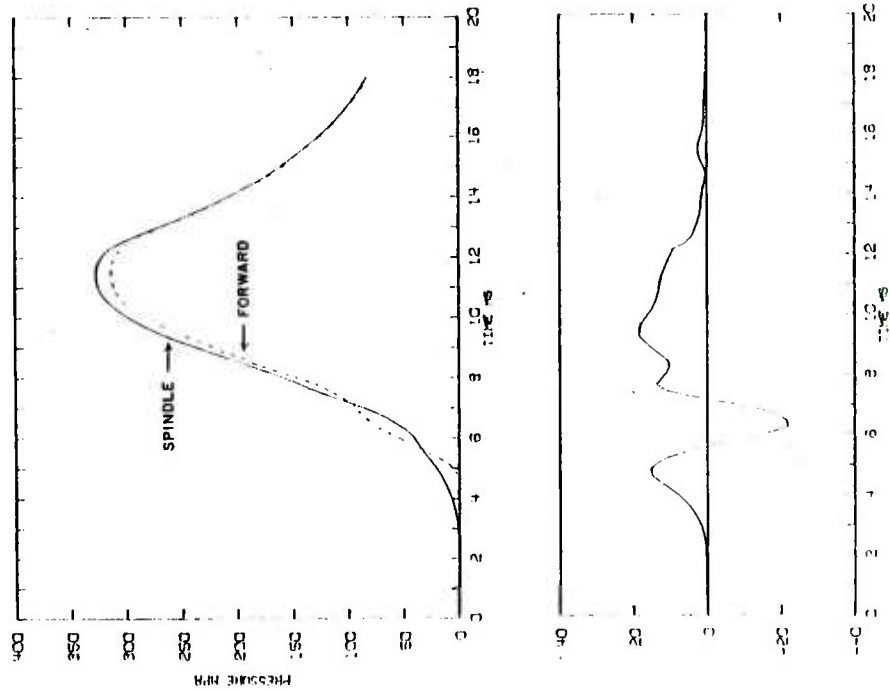
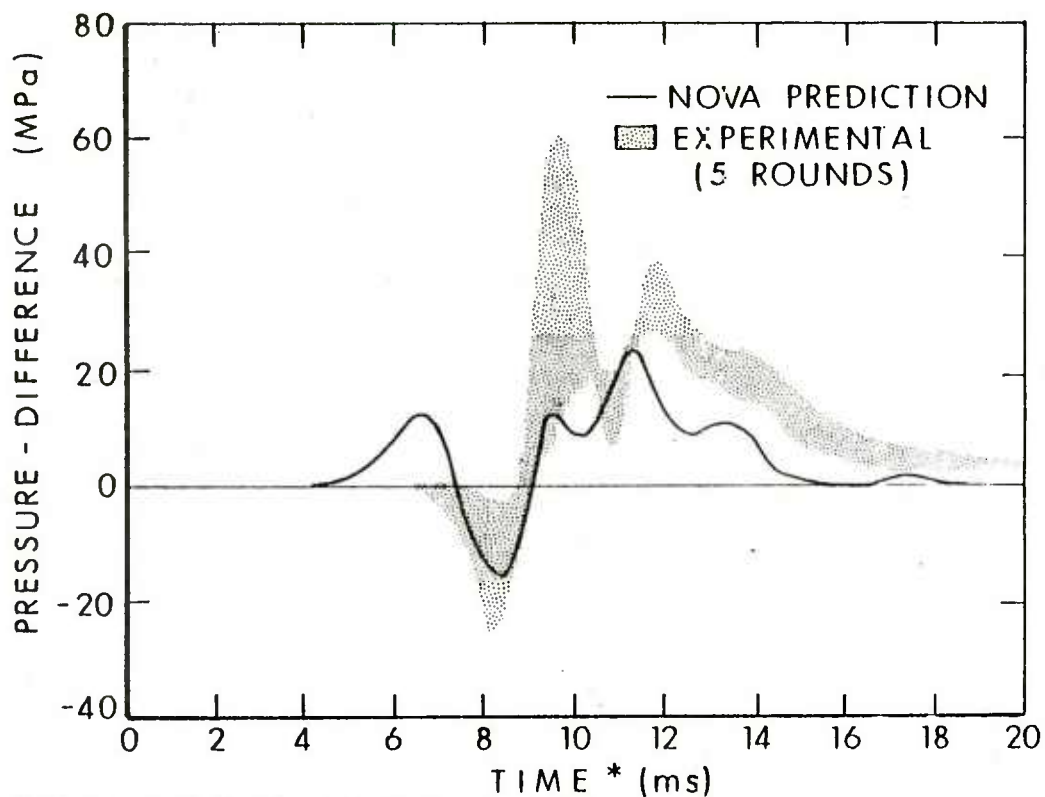
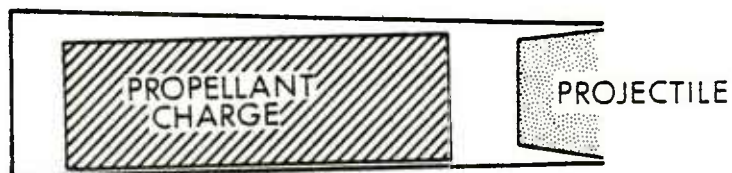


Figure 12. NOVA Simulation, M203
Propelling Charge, 25-mm Standoff



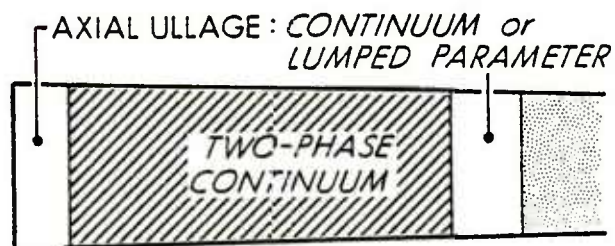
* ADJUSTED ZERO-REFERENCE TIMES

Figure 13. Comparison of Predicted and Experimental Pressure-Difference Profiles, M203 Propelling Charge, 25-mm Standoff



ACTUAL BAG CONFIGURATION

Figure 14. Schematic Representations of Bagged-Charge Configuration



QUASI-ONE-DIMENSIONAL REPRESENTATION

short ignition delays (~ 5 ms). Additional major contributors to the real-world delay (~ 60 ms) may be the bag and associated parasitic components themselves. Burn-through and rupture of the bag are, of course, not included in the one-dimensional representation. As a result of this predicted, rapid ignition of the rear of the main charge, input data reflecting functioning of the igniter centercore are of no consequence, as they represent igniter output after flamespread throughout the bed has been calculated to be complete. Hence, NOVA predicts a monotonic propagation of flame forward through the bed, accompanied by a strong stagnation at the projectile base.

Largely in response to problems such as this, a two-dimensional, axisymmetric flamespread model has been developed, but as of yet is limited to solution of a single region of flow with no explicit recognition of internal boundaries. A quasi-two-dimensional code has, however, been implemented by Gough³¹ for the study of bagged charges. This analysis assumes that the gun chamber can be divided into disjoint but coupled regions, the flow in each of which can be treated as one-dimensional (see Figure 15). Results from calculations using this code, depicted in Figures 16 through 18, suggest that flow around the bag can significantly alter the flame path and even reduce large pressure gradients that might otherwise develop early in the ballistic cycle. Thus both initial charge dimensions and material characteristics might be expected to be potentially important design parameters with respect to pressure waves.

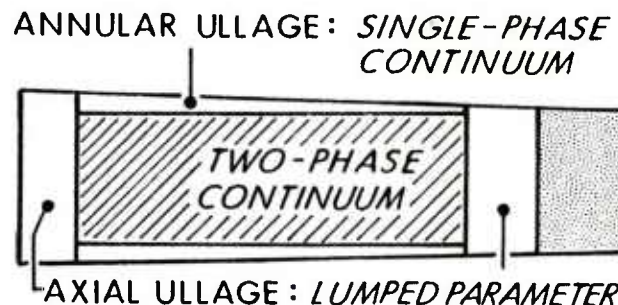


Figure 15. Quasi-Two-Dimensional Representation of Bagged-Charge Configuration

³¹P. S. Gough, "Theoretical Study of Two-Phase Flow Associated with Granular Bag Charges," ARBRL-CR-00381, USA ARRADCOM, Ballistic Research Laboratory, Aberdeen Proving Ground, MD, September 1978. (AD#A062144)

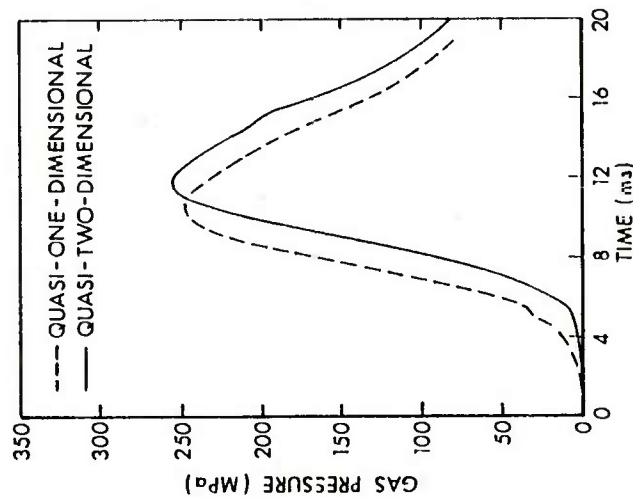


Figure 16. Comparisons of Predictions of Breech Pressure According to Quasi-One-Dimensional and Quasi-Two-Dimensional Calculations (from Ref. 31)

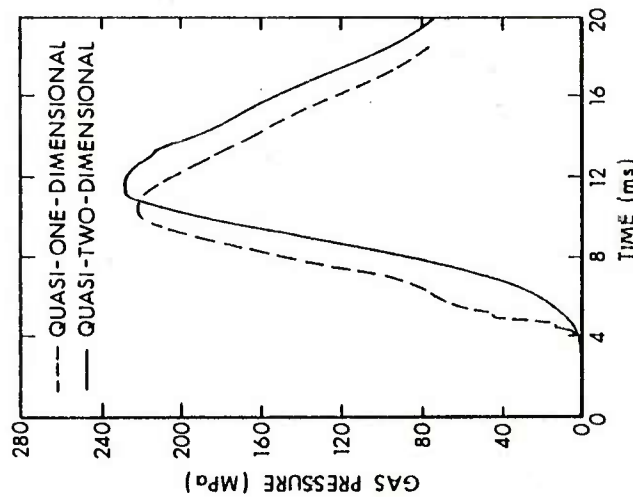


Figure 17. Comparison of Predictions of Base Pressure According to Quasi-One-Dimensional and Quasi-Two-Dimensional Calculations (from Ref. 31)

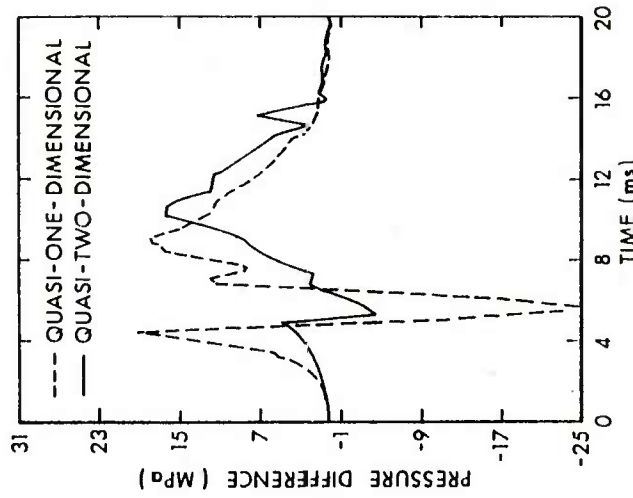


Figure 18. Comparison of Predictions of Pressure-Difference History According to Quasi-One-Dimensional and Quasi-Two-Dimensional Calculations (from Ref. 31)

E. Identification of Critical Experiments

Since many of the input data used in two-phase flow interior ballistic modeling are not well known, a number of critical studies must be undertaken to supply required information both to guide future model development and to aid in model evaluation. Some of these data gaps are applicable to classical, lumped-parameter codes as well. Heretofore, there has been a dearth of reliable burning rate data for gun propellants, particularly for Army triple-base propellants (such as M30A1). The burning rate, long one of the parameters most often varied to match experimental performance with lumped-parameter codes, is of even greater importance when it comes to predictions of flamespread and pressure waves. The other great "classical input variable" has been the bore resistance profile. Data for resistance to projectile motion, applicable to the dynamic gun environment, are needed to model the early portion of projectile travel, significantly affecting predicted peak pressures through its impact on available free volume. While not as well documented, such data can also dramatically affect predictions of pressure waves. Attempts at dynamic modeling of resistance have had indifferent success.

More pertinent to the topic of this report, however, are those characteristics or processes singular to bagged-charge configurations. For instance, specific properties of the bag material itself, such as permeability to gas flow, combustion properties, and rupture characteristics, are essential parameters to developing an understanding of the basic phenomenology of bagged charges. Very little is known in this area, though some testing is in the planning stages. Looking at the bigger picture, the geometric effects associated with the time-dependent configurational constraints imposed by the propellant bag must also be investigated. Possible effects on bed mobility, annular ullage, and combustion species confinement have been previously mentioned. Included in the studies must be those aimed at directly assessing the adequacy of 1-D and 2-D approximations. It must be pointed out, however, that even a full 3-D representation will not provide successful simulations of bagged-charge performance without key constitutive physical data such as those mentioned above.

III. EXPERIMENTAL

A. Apparatus

To validate various interior ballistic models, and to guide future model development, the apparatus shown in Figure 19 was designed and constructed at the Ballistic Research Laboratory. It is in many respects similar to the setup at the Naval Surface Weapons Center (NSWC)²⁴⁻²⁶, Dahlgren, the prime difference being that the NSWC fixture is vertical while the BRL apparatus is horizontal, to approximate more closely the attitude employed in most artillery testing. The heart of the system is a filament-wound fiberglass tube which simulates the chamber of the 155-mm, M199 Cannon of the M198 Howitzer. The bore of the fiberglass

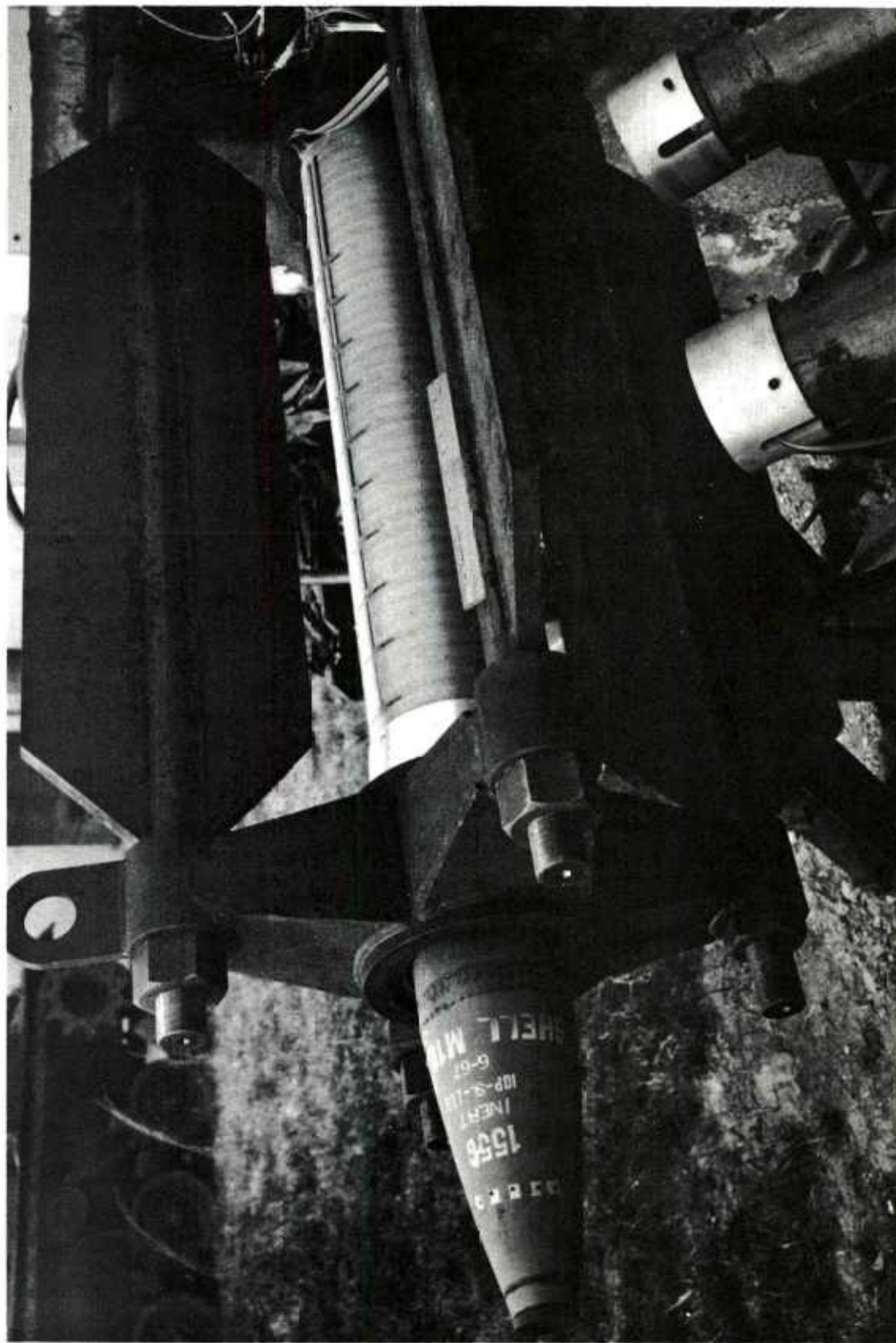


Figure 19. Photograph of Experimental Apparatus, 155-mm Fiberglass Chamber

chamber is tapered at 0.01 mm/mm, as is the M199. For the tubes employed to date, the wall consists of an interior buildup of 1.52 mm of ± 80 -degree wrap, with the remainder of the radius wrapped essentially in the hoop mode. The wall thickness, 9.65 mm, is small enough to transmit high-intensity light to monitor flamespread, and X-rays to monitor propellant grain and other charge component motion. To measure pressure-front propagation, strain patches are affixed in pairs at ten locations in 76.2-mm intervals along the exterior of the tube. Figure 20 shows this, as well as the location of up to three piezo-electric pressure transducers in the modified M199 spindle, which is used to close the breech end of the tube. The muzzle end is closed by a projectile inserted in a section of simulated M199 forcing cone and rifling, which is bolted over the end of the fiberglass tube. The projectile may include onboard instrumentation.

Photographic data are recorded with two Hycam 40, high-speed, 16-mm cameras. Typically, one camera is run at 5000 pictures per second (pps), full frame and the other at 10,000 pps, half frame. Again typically, Kodak Ektachrome 7241 film is used to record the event, and the 10,000 pps film is push-processed by two f-stops to improve readability. A 1-KHz timing signal is put on each of the films by electronics internal to the cameras, and the firing fiducial (time firing voltage is applied to the cannon) is also placed on the films to correlate the film data with other data.

When used, X-rays are recorded on cassettes placed opposite the tube from orthogonal X-ray heads. The tubes are driven by a 300-kilovolt, dual-flash system. The radiographs are recorded on medical X-ray film using image intensifier screens. The geometry of the apparatus is currently such that orthogonal X-ray data and high speed photographic data cannot be taken on the same shot. Since two dynamic radiographs are required to determine grain velocities, these measurements have not yet been made.

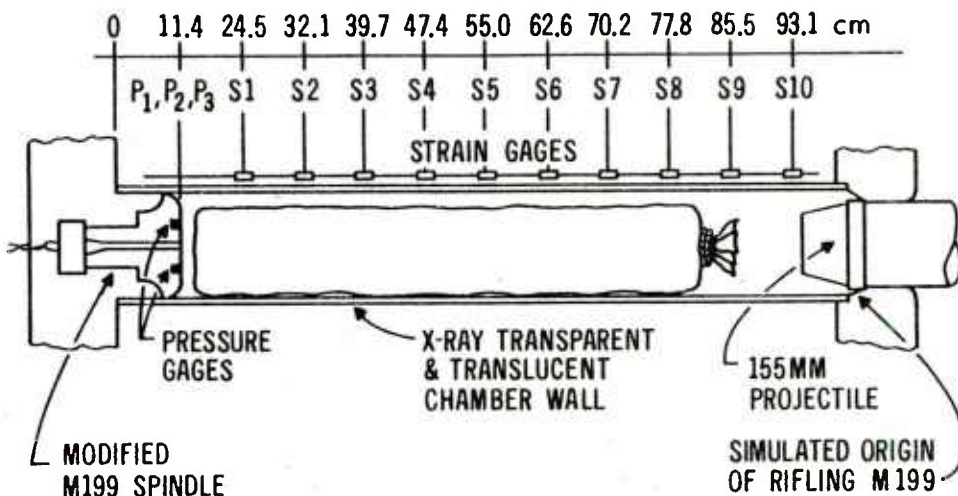


Figure 20. Schematic of 155-mm Fiberglass Chamber

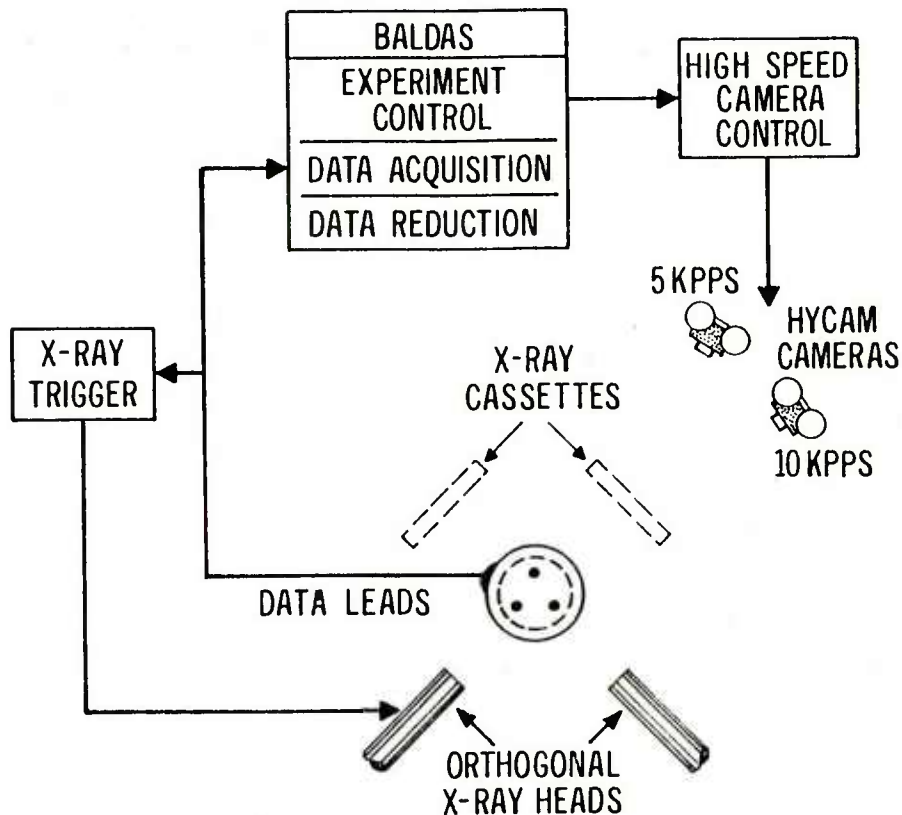


Figure 21. Instrumentation, Experiment Control, and Data Acquisition for 155-mm Fiberglass Chamber Test System

Figure 21 depicts the system for experiment control, data acquisition, and data reduction. The Ballistic Data Acquisition System (BALDAS) performs these tasks, driven by a PDP 11/45 mini-computer. By starting a programmed sequence timer, BALDAS controls the firing of the high speed cameras and enables an X-ray trigger circuit. At the appropriate time, BALDAS exercises an in-line, five-step, calibration for each data channel, then fires the cannon and acquires and digitizes analog data through a 16-channel, 10-bit, 2⁴-K word analog-to-digital converter. At the same time, a backup analog record is made on one or two 14-channel FM tape recorders. BALDAS-resident digital counters record the time of the firing fiducial and other events, such as an X-ray trigger pulse.

After the data are acquired, BALDAS calibrates the data via a second-order, least-squares fit to the calibration staircase, and then reduces the data, through suitably introduced gage constants. Data are displayed on plots or in a point-by-point listing of the digital record.

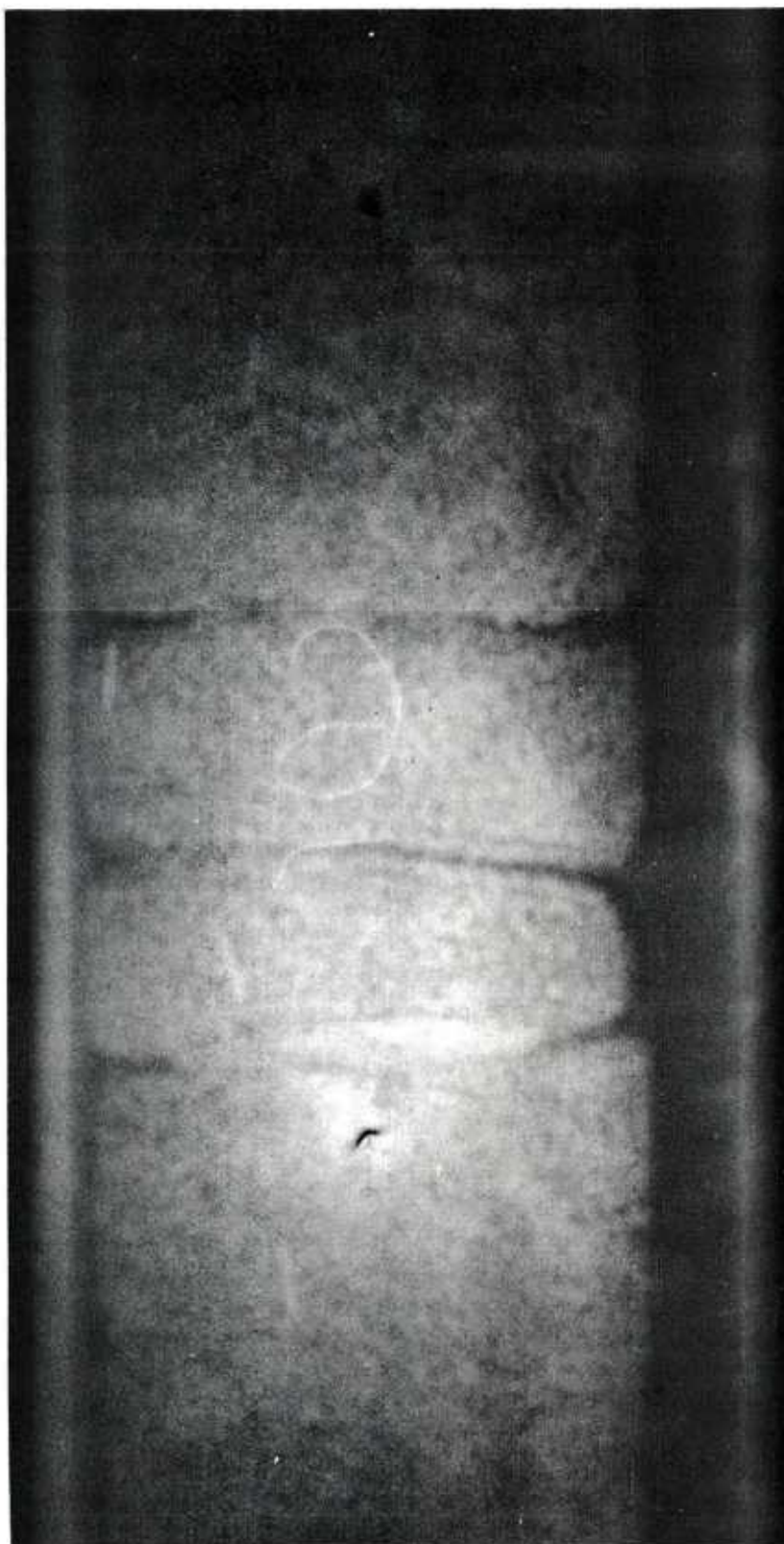


Figure 22. Static Radiograph of M4A2 Propelling Charge in 155-mm Fiberglass Fixture

To date, no dynamic X-ray data have been taken for the purpose of measuring propellant grain motion, although single, dynamic radiographs have been recorded. Figure 22 shows a still radiograph of an M4A2 Charge in the fiberglass chamber. The charge consists of five easily discernible zones of M1 propellant, with grains approximately 10 mm long and 4.5 mm in diameter. Other points of interest are the flash reducer bag and the high density brass marker rods. The rods are imbedded in propellant grains to monitor grain motion during an interior ballistic cycle.

Eleven rounds were fired in the fiberglass fixture. A number of these were conducted with reduced charges to debug instrumentation, select appropriate parameters for on-line data acquisition, and so forth. In the following, a discussion of two of these checkout shots, a full-bore charge and a sub-caliber charge, is provided since they reveal some interesting characteristics of flamespread and charge motion. Results are then provided from two base-ignited, 155-mm, M203 shots.

B. Results

1. Full-Bore Charge. Figure 23 is a schematic of a short, one-dimensional charge consisting of approximately 3.10 kg of M1 propellant from a 155-mm, M4A2, Charge ignited by 85 g of Class 1 black powder. The charge is full bore, with the indicated axial ullage between the front of the charge and the projectile base. A portion of the flame data abstracted from the high-speed films is shown in Figure 24. Initially, there was a faint glow at the spindle, followed by flame at the projectile base, probably due to a stagnation of igniter gases. The charge as a whole was then propelled down the chamber and impacted upon the projectile, with a velocity of about 15 m/s upon impact. No flamespread through the charge proper was observed.

As a further test and demonstration of this charge motion, an inert charge of the same size and weight was loaded with a live basepad similar

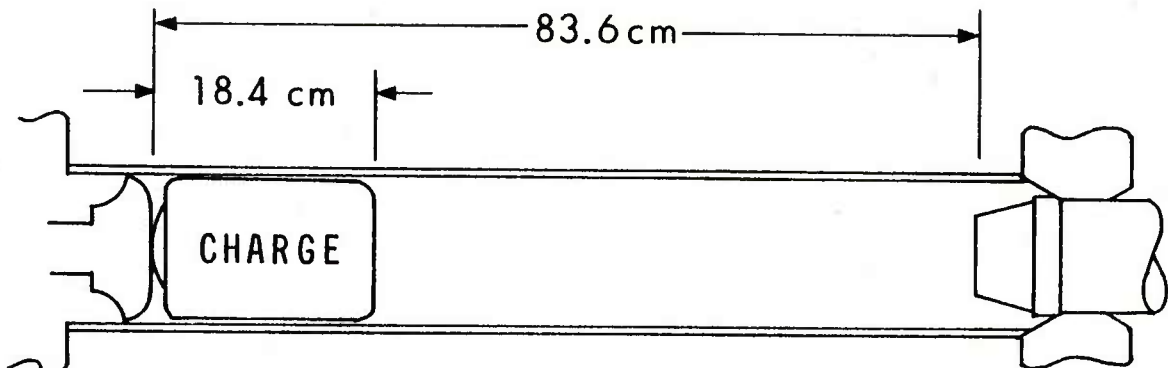


Figure 23. Modified M4A2, Zone 5, Full-Bore Charge in 155-mm Fiberglass Chamber Before Firing



Figure 24. Film Flame Data, Modified M4A2, Zone 5, Full-Bore Charge

to that used previously. After the shot, the apparatus was disassembled, and the charge, which initially occupied the rear 18.4 cm of the tube, was compacted against the projectile base to approximately half this length. A photograph of the front end of the tube is shown in Figure 25. Many of the propellant grains were shattered, and the front of the bed was molded to the shape of the base of the projectile. The front and rear ends of the bag were consumed, but the sidewall length of the bag was accordion-folded.

Wires et al³² have run comparison mechanical properties tests of this inert propellant and M30. The bulk modulus of the inert propellant is



Figure 25. Inert, Full-Bore Charge in 155-mm Fiberglass Chamber After Firing

³²R. A. Wires, J. P. Pfau, and J. J. Rocchio, "The Effect of High Rates of Applied Force and Temperature on the Mechanical Properties of Gun Propellants," CPIA Publication 300, Proceedings of the 1979 JANNAF Propulsion Meeting, March 1979.

substantially higher than that of the M30, and the "toughness", a measure of the energy required to deform the material to maximum stress, is comparable. It thus appears that grain fracture of a magnitude found in this inert test may occur in an actual interior ballistic environment.

2. Sub-Caliber Charge. Another type of checkout round consisted of 0.74 kg of the M1 propellant discussed previously, again ignited by the 85 g, black-powder basepad. The charge was loaded in a bag approximately 41 cm long and 7.6 cm in diameter. The sub-caliber charge was placed on a polyurethane cruciform spacer to align it with the spithole, the result being a nearly two-dimensional, axisymmetric configuration. A schematic of the charge is given in Figure 26. Film data from one of these shots are shown in Figure 27. The luminous front took approximately 1.7 ms to traverse the chamber, with film frame-to-frame velocities in the range 300-400 m/s. Of particular note here is the reflection of the luminous front, not seen in other published flamespread photographs. These results can be interpreted as an acoustic wave, or, since the fiberglass tube and front seal survived the pressure wave reflection off the projectile, a rearward-moving pressure front, locally augmenting burning of the partially consumed solid propellant or propellant gases and increasing the luminosity with the results shown.

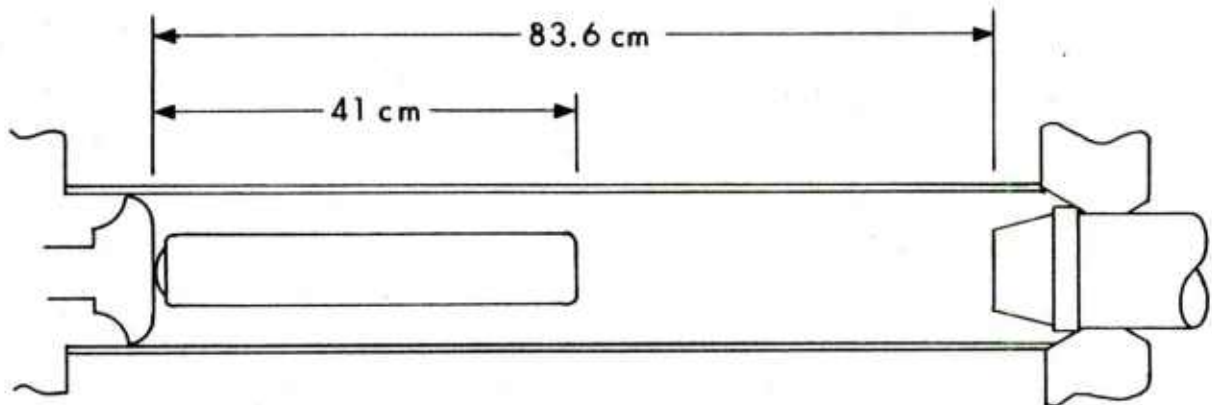


Figure 26. Sub-Caliber Charge in 155-mm Fiberglass Chamber Before Firing

3. Base-Ignited, Asymmetrically Loaded M203 Charge A photograph of the charge, with modifications noted, is provided as Figure 28. The charge, from Lot IND-77B-000E36, had its centercore ignition system defeated by emptying the black powder from the snake, wadding the snake bag up and placing it in the centercore next to the basepad. This modification was introduced to assure strong, localized ignition at the base of the charge. The lead foil, wear reducing additive, and the flash reducer bag were all removed. The length of charge thus modified was 76.8

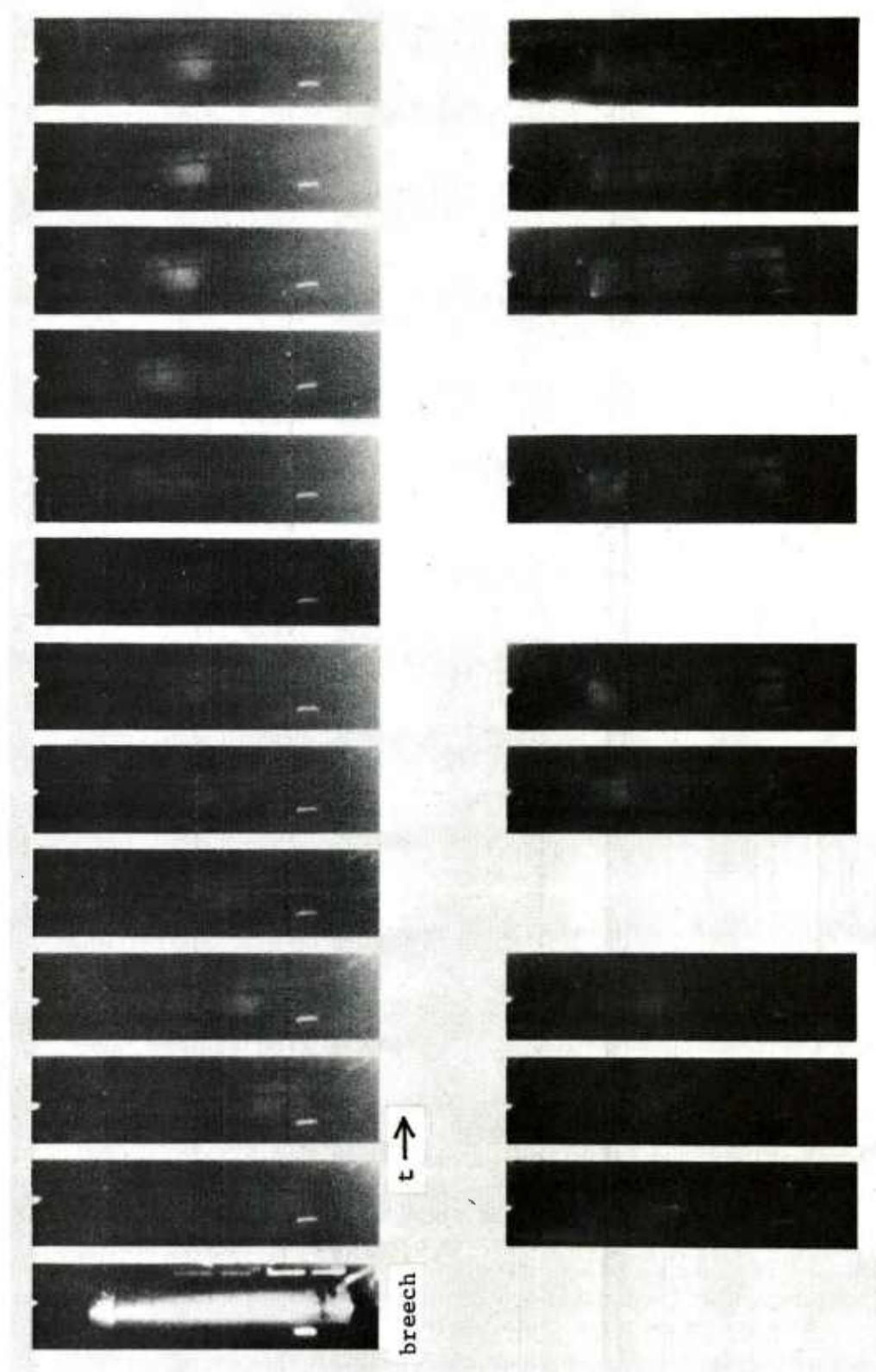


Figure 27. Film Flame Data, Sub-Caliber Charge

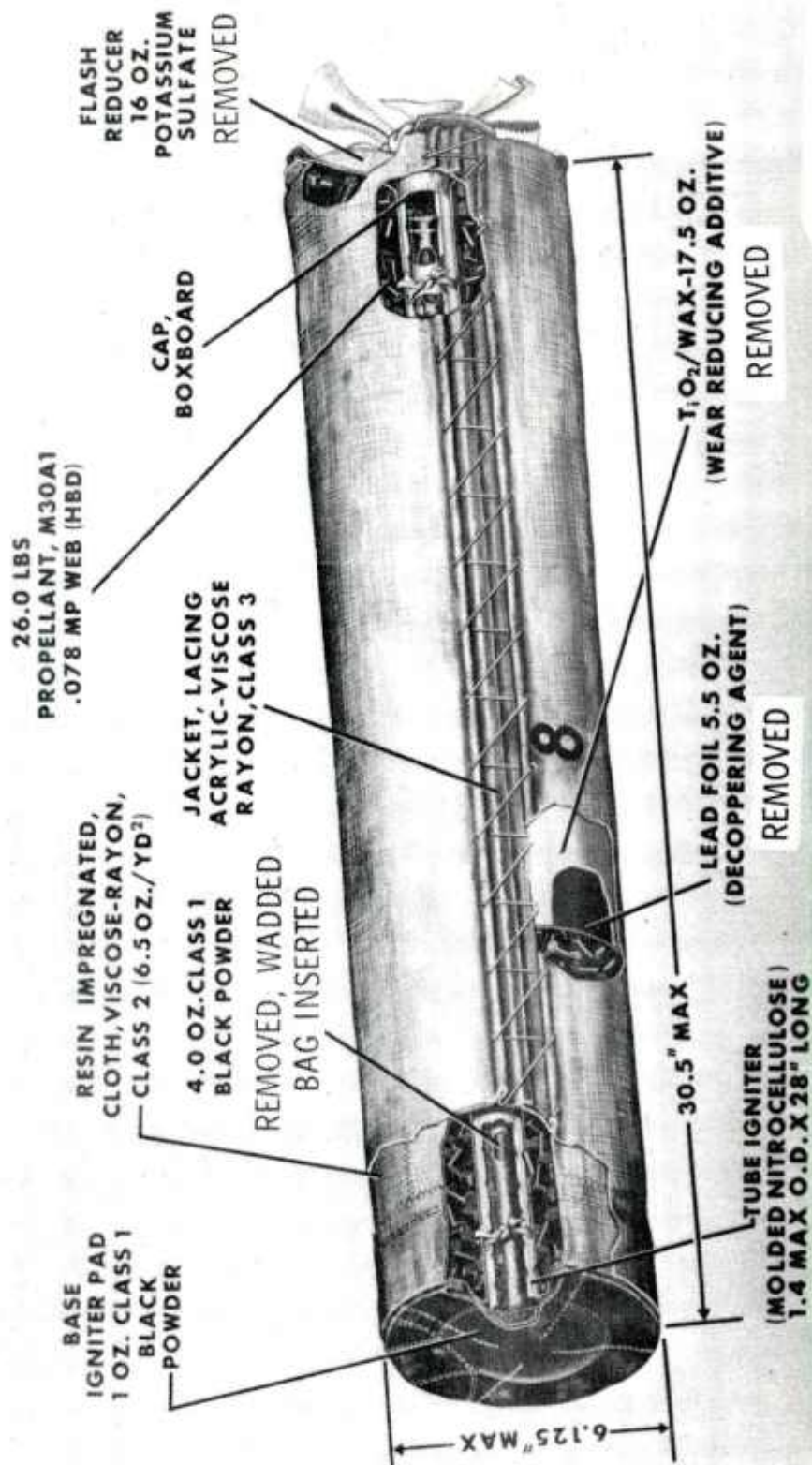


Figure 28. 155-mm, M203, Propelling Charge, Modified for Base Ignition

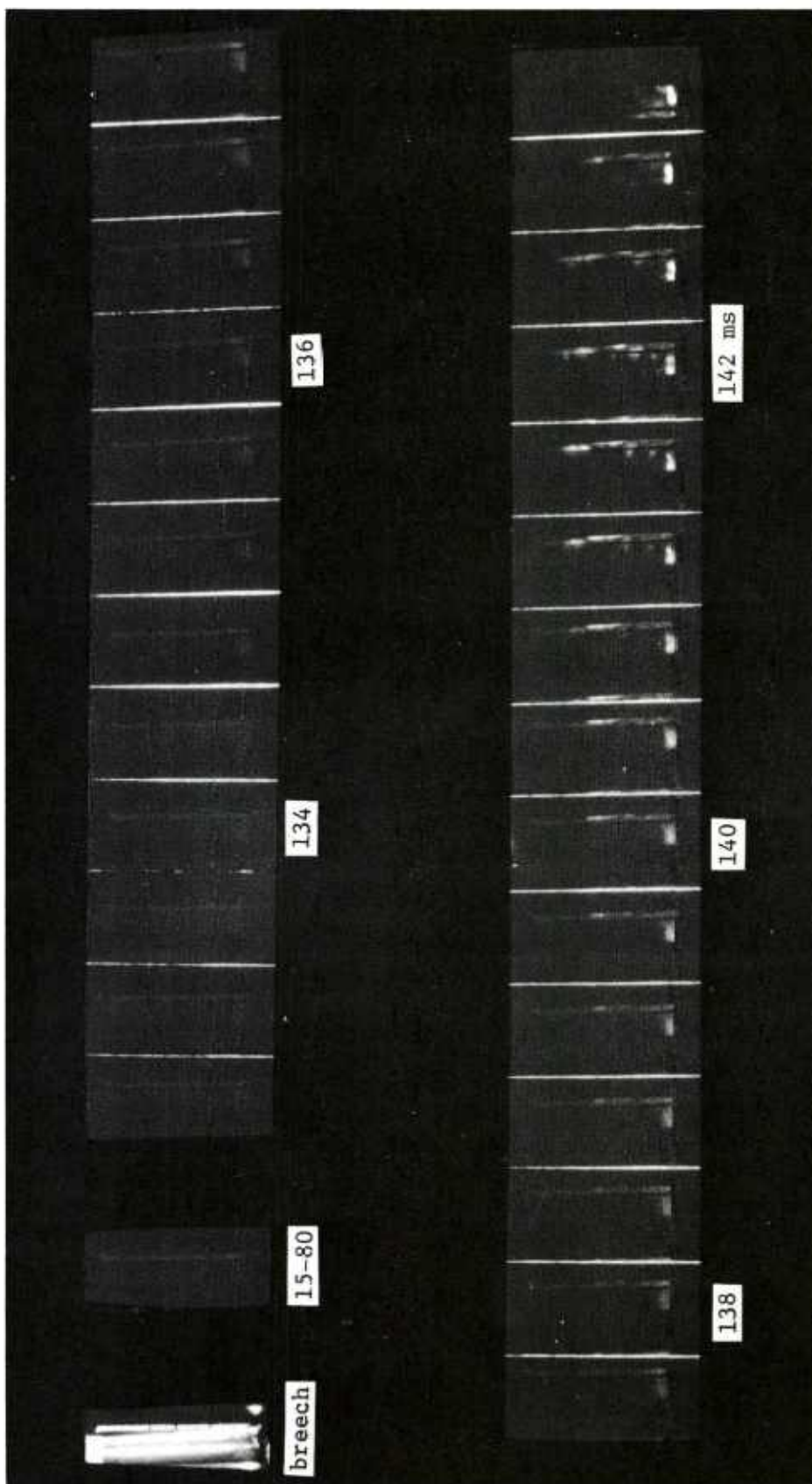


Figure 29. Film Flame Data, Base-Ignited, Asymmetrically Loaded M203 Charge

cm. The charge was loaded with no standoff, on the bottom of the chamber with approximately 13 mm ullage at the top, front portion of the charge. The axial ullage at the front of the charge was 12.2 cm. During the shot, the tube fractured, and pressure data were lost just prior to the time of maximum $-\Delta P_i$. High-speed film data were recorded, but flamespread data were not interpreted from them, due to the unconventional flow seen. A schematic of the flame data abstracted from the high-speed films and annotated with event times, is given in Figure 29. From approximately 15 to 80 milliseconds after the firing voltage was applied to the gun, a glow from the primer and basepad was seen. This died out during the ignition delay. Then the basepad/charge began burning, and the charge was propelled forward in the chamber. Without any appreciable, observable, flamespread into the charge, flame ran along the top of the charge to the forward area of the chamber. At this point the data were obscured by a leaking front seal.

Figure 30 presents the pressure profiles in the chamber. It should be noted that the local maximum in the pressure profiles near the forward end of the chamber may reflect response of the strain gages to intergranular stress resulting from compaction of the charge in the front of the chamber, since propagation typical of a traveling pressure wave is not observed. The magnitude of the local maximum may not be reliable due to a leaky front seal. Physical intuition as well as the quasi-two-

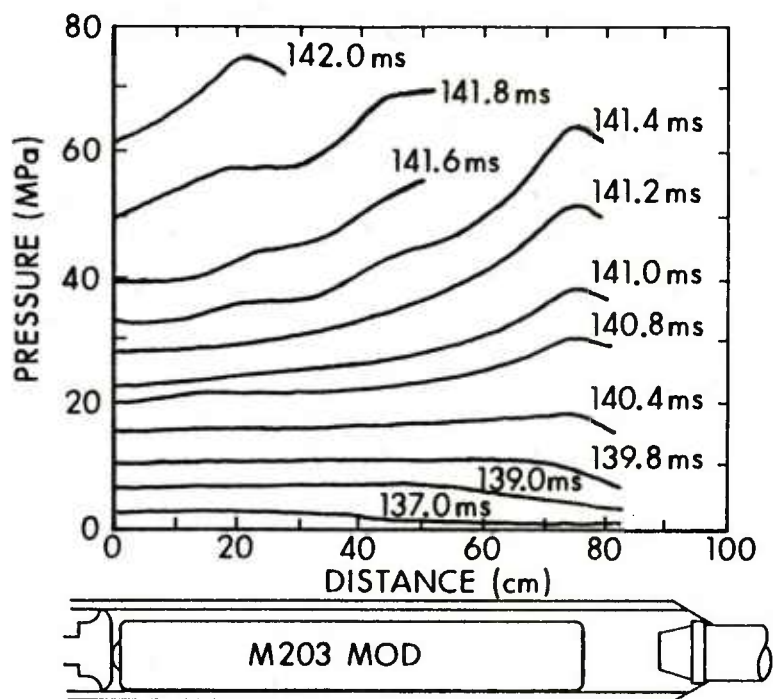


Figure 30. Pressure Profiles, Base-Ignited, Asymmetrically Loaded M203 Charge

dimensional results of Gough³¹ appear to be borne out by this 3-D, base-ignited M203 firing. The flame front stalled in the charge while the flame took the path of least resistance via the ullage at the top of the charge. If the rear-facing pressure gradient arose from a gas pressure rather than granular stresses in the vicinity of the projectile, then ignition/combustion of the forward end of the charge may be indicated by the pressure profiles. The presence of a rear-facing gradient of any significant magnitude, be it gas or solid phase, indicates that the radial ullage present during the forward gas flow did not persist, perhaps owing to bag rupture with subsequent radial dispersion of the propellant.

4. Base-Ignited, Axisymmetrically Loaded, M203 Charge. An M203 charge, modified as described in the previous section, was loaded axisymmetrically into the fiberglass chamber such that there was approximately 7 mm radial ullage around the entire charge at the forward edge. The charge was loaded with no standoff, and there was the same axial ullage at the front of the charge as previously noted.

A portion of the film data is provided in Figure 31. As before, luminosity was seen from the primer function over the same time range. The luminosity died out during the ignition delay, luminous gases from the basepad were seen, and the charge was pushed forward in the chamber as before. No flow was seen through the ullage, though the flame undoubtedly spread through the charge but was obscured by the bag. A luminous region opened just forward of the rear of the charge, as might be expected with bag rupture, and a portion of the charge was pushed toward the spindle, followed by luminosity spreading to the spindle until the data were lost.

The pressure profiles for this shot are presented in Figure 32. The only substantial structure seen on the profiles is in the vicinity of the hypothesized bag rupture. This bag rupture is accompanied by a nearly coincidental minimum in local pressure, possibly related to effects of separation and propulsion of a portion of the charge rearward. A local maximum in this area is noted after combustion is well underway.

It should be noted that the break in the bag is in the area where the cloth had previously been sewn at the rear edge of the lead and wear-reducing liners. In removing these parasitics, the cloth was not cut, but stitching had been removed, perhaps weakening the bag.

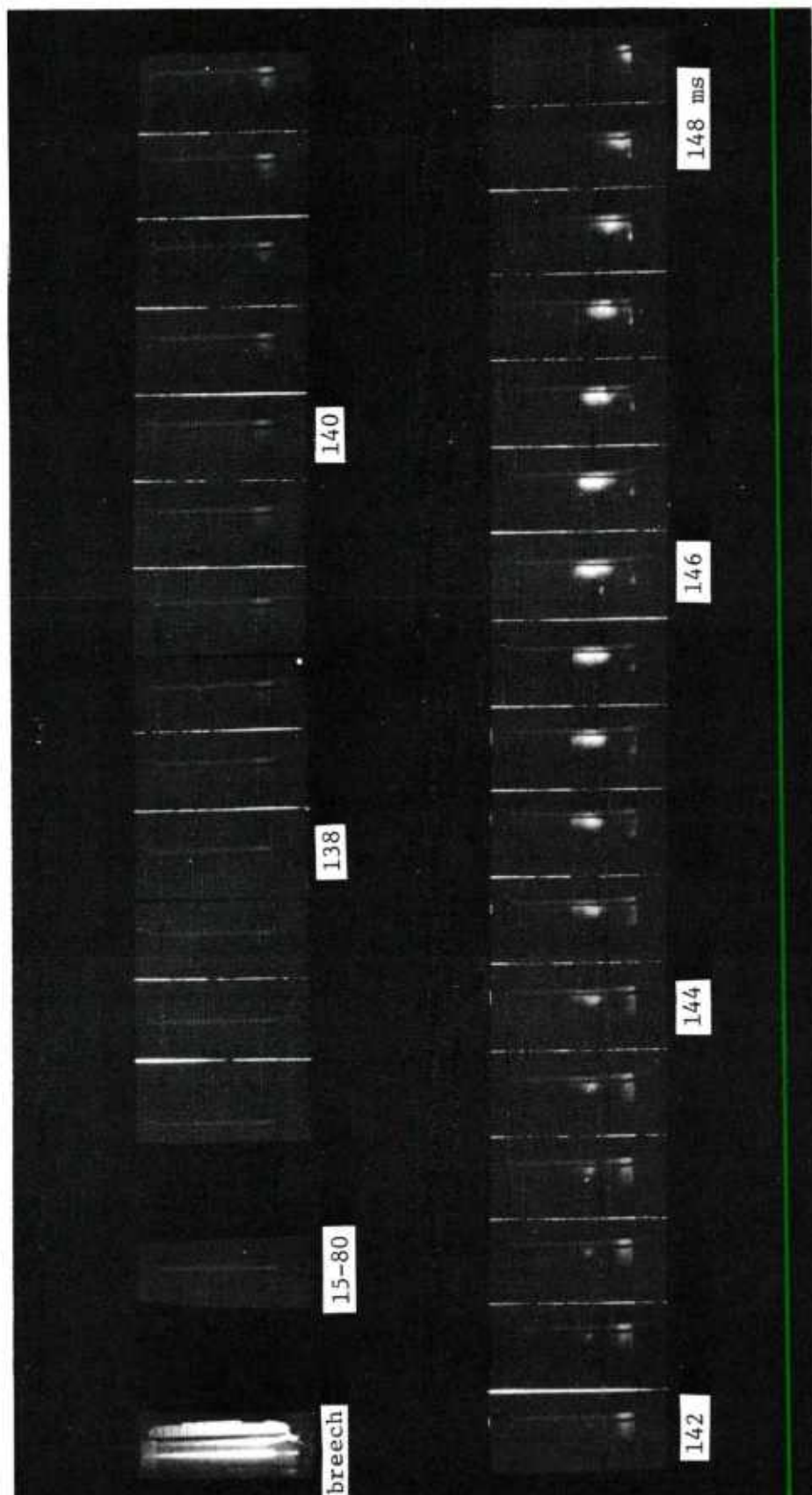


Figure 31. Film Flame Data, Base-Ignited, Axisymmetrically Loaded M203 Charge

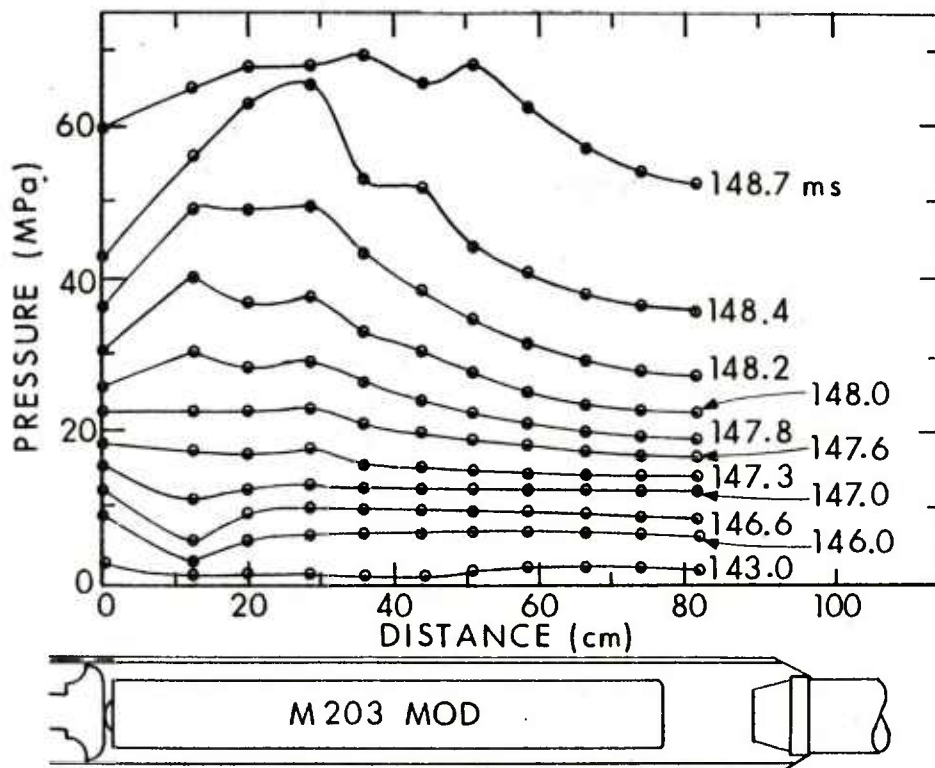


Figure 32. Pressure Profiles, Base-Ignited, Axisymmetrically Loaded, M203 Charge

IV. CONCLUSIONS

It is apparent that many of the properties peculiar to bagged charges need to be taken into greater consideration by the charge designer than is customarily the case. The igniter itself usually, though not always, receives sufficient attention in the design of a new charge, yet any of these other parameters - bag material, charge geometry, ullage distribution, and parasitic component characteristics - can seriously affect igniter performance, even defeating its intended mode of operation. Looking at the situation in a more positive light, these other factors should be considered as important elements of the overall ignition system, available to be exploited for design optimization of both safety and performance.

Further, these results suggest that the successful implementation of useful, multi-dimensional interior ballistic codes will require an explicit recognition and treatment of the influence on flamespreading of bag materials, liners, and additives.

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